



Fresnel lens fabrication for broadband IR optics using hot embossing process



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HIGHLIGHTS

- Hot embossing process for Fresnel lenses fabrication from multi-component glasses.
- Selecting glass considering: transmittance, resistance to crystallization, adhesion.
- We select the lead–bismuth–gallium oxide glass.
- Effective focusing light in the visible and in mid-infrared range.

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ABSTRACT

The aim of the paper was to examine the possibility of fabrication of glass diffractive optical elements that work within near and mid-infrared. The paper focuses on the results of fabrication of Fresnel lenses with the use of hot embossing process from multi-component glasses. In the experiment lead–bismuth–gallium oxide and tellurite glasses were used, which are characterized by high transmittance within the visible light spectrum to mid-infrared (6.5 μm). As the mold a fused silica element was used, which had been fabricated with the standard method of ion etching. The elements presented were fabricated in a static process with the use of low pressure. The quality of the fabricated elements was examined with white light interferometer. The fabricated Fresnel lenses can be used in directing light within the visible spectrum up to c.a. 6 μm into optical fibers and in beam collimation at the output of the optical fiber.

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1. Introduction

For the last decade we have witnessed a dynamic development of research and applications of optoelectronics within the infrared (2–14 μm) spectrum. Within this range there are transmission windows in the atmosphere of the Earth and vibration bands of many kinds of bonds in chemical organic compounds [1]. For this reason optical setups working within mid-infrared have found numerous applications from optical telecommunication in free space, through spectroscopy, medicine and dental applications, instrumentation, biotechnology, tomography, thermal imaging up to military defense devices. The main problem of such setups is their high cost resulting from the price of the passive optical elements such as lenses. So far, most of the optical components working in mid-infrared range were based on single crystalline germanium (Ge) or zinc selenide (ZnSe). For their production a costly single-point diamond-tuning process [2] is used. That is why it is important to develop new materials and technologies which will allow for the low-cost fabrication.

One of the solutions for lens fabrication is the use of materials whose formation will involve the hot embossing process [3]. Such materials include standard chalcogenide glass compositions made of germanium arsenic selenium ($\text{Ge}_{22}\text{As}_{20}\text{Se}_{58}$ or GASIR1) and germanium antimony selenium ($\text{Ge}_{20}\text{Sb}_{15}\text{Se}_{65}$ or GASIR2) [4]. However, such glass is poisonous, relatively expensive and, most importantly, not transparent within the visible light range, which excludes some applications. Also, apart from lenses, there are no other passive optical elements available; especially there are no diffractive optical elements (DOEs). An inexpensive material easy to process is polymers used to produce diffractive elements, but they too have their disadvantages. Most importantly, it is their liability, low thermal durability and the change of their optical parameters over time [4].

Diffractive optical elements (DOEs) are thin optical phase objects which operate on light diffraction and interference [5]. An example of DOE are Fresnel lenses, which can be used to form the light beam, similarly to common refractive lenses. What differentiates them from the refractive lenses is their thickness that can be comparable to the length of the light wave. Thanks to that they have found applications in contemporary optics, physics and engineering. For instance, they allow for the production of smaller,

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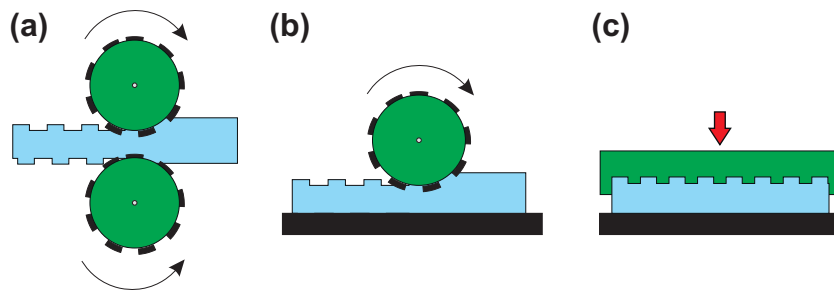


Fig. 1. Basic types of the hot embossing process.

Table 1
Parameters of the glasses considered for the experiment.

Parameter	Glass symbol					
	LW-1	PBG08	PBG05	TWNB-1	TWPN/I/6	TCG75921
n_d	1.846	1.938	2.350	2.155	2.149	2.170
α (10^{-6} K^{-1})	8.31	8.30	11.05	15.51	14.40	10.78
DTM ($^{\circ}\text{C}$)	420.0	500.0	468.5	368.0	385.0	392.2
Temp. ($^{\circ}\text{C}$)						
T_g $\log \eta = 13.4$	400.0	463.2	443.0	355.9	365.0	368.5
T_z $\log \eta = 9.0$	421.0	542.0	490.0	370.0	395.0	395.0
T_k $\log \eta = 6.0$	450.0	615.0	540.0	395.0	415.0	445.0
T_{pk} $\log \eta = 4.0$	487.5	690.8	575.0	440.0	460.0	485.0
T_r $\log \eta = 2.0$	645.0	800.5	680.0	510.0	535.5	560.0
d (g/cm^3)	5.625	5.798	8.020	5.795	5.881	7.410
Transmission (nm)						
–Lower limit	380	380	460	425	420	460
–Upper limit	3700	5200	8000	6700	6850	7400
A (dB/m)	No data	5–2200	No data	No data	No data	16–2100

n_d – refraction index (d -line), α – linear thermal expansion coefficient (20–300 $^{\circ}\text{C}$ range), DTM – dilatometric softening point, T_g – transition temperature, T_z – ovalization point, T_k – sphere point, T_{pk} – hemisphere point, T_r – spreading point, d – density, A – attenuation.

more compact camera lenses and for increasing the effectiveness of the solar cells.

There are many ways of producing DOE. One of the cheapest is the above mentioned hot embossing, suitable for both small-scale and massive production. The method is especially appropriate for fabricating polymer microoptical elements [3,6,7], and is also used in microlens fabrication in metallic glass [8]. The hot embossing method can also be used with glass, but this involves several problems of technical kind. First, the process requires higher temperatures. Whereas in the case of polymers the process needs the maximum of about 200 $^{\circ}\text{C}$ (e.g. 180 $^{\circ}\text{C}$ for PC and more than 200 $^{\circ}\text{C}$ for polymers for thermal nanoimprint lithography [9]), in the case of glass the temperature required is 400–900 $^{\circ}\text{C}$, depending on the composition of the glass used [6–8,10]. Secondly, the process requires better temperature stabilization to make the hot glass malleable but not molten and it would not undergo crystallization.

In practice, three basic variants of the hot embossing process are used [3,6–8]: multiplication of the pattern via rolling the material through two master forms (Fig. 1a), rolling the substrate through the master form on a flat surface of the mold (Fig. 1b) and imprinting a flat mold on the surface of the substrate (Fig. 1c). The first two methods are commonly used when the material to be formed is plastic enough and they allow for massive fabrication of the consecutive elements. The third method allows development of elements made of less plastic materials as glass, where thermal processing requires longer time.

In all the methods mentioned it is crucial to choose the mold material according to the type of glass in order to reduce the mutual corrosion of both materials [3]. Additional limitations stem

from the mechanical and thermo-chemical properties of glasses. Only glasses characterized by high resistance to crystallization can be processed. Also the right rheology is important and fitting the thermal expansion coefficients to the mold material within the processing temperature range as well as below the temperature of the transformation [3]. It is especially important in the case of DOE element fabrication, where the wrong choice of the thermal expansion coefficients leads to stress, which results in cracking and in the destruction of the delicate pattern on the glass surface.

2. Material choice

For technological tests we chose glasses which were potentially suitable for the visible spectrum and mid-infrared. These were glasses composed of three to six oxides in varying proportions: SiO_2 , PbO , Bi_2O_3 , Ga_2O_3 , CdO , B_2O_3 , ZnO , Ti_2O_3 , GeO_2 , WO_3 , Na_2O ,

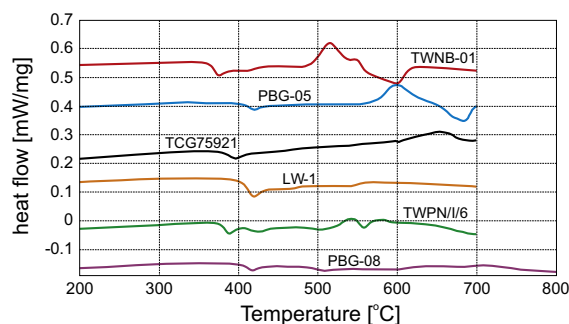


Fig. 2. Curves of differential scanning calorimetry of the considered glasses.

TeO_2 and Nb_2O_5 . As a glass selection criteria we used transmission properties in infrared region, adhesion between glass and the mold insert, as well as the viscosity characteristic and resistance to crystallization. In addition we took into account also cost and availability. The summary of the basic characteristics of the glasses considered is presented in Table 1.

As the coefficient of resistance to crystallization we used the characteristics of the curves of differential scanning calorimetry (DSC) [11] – Fig. 2. DSC is a technique which enables a measurement of the amount of heat required to increase the temperature in relation to the reference model. During the experiment both the sample and reference are maintained at nearly this same temperature. The temperature increases linearly as a function of time. When the sample undergoes a physical transformation such as phase transitions, it may need to absorb or emit heat in order to maintain the same temperature as the reference. Significant exothermic peaks that appear on the thermogram allow estimating the possibility of phase transitions such as the crystallization of the glass. The thermogram of six kinds of glass gained from NETZSCH STA 449F1 in heat flow (mW/mg) as a function of temperature ($^{\circ}\text{C}$) is presented below. The endothermic dip observed for every glass around the temperature 400°C is a result of the heat flow changes related to glass melting. The further shape of the DSC curve for glass not liable to crystallization should not exhibit large changes. Glasses TWNB-01, PBG-05 and TWPNI/6 do not meet these criteria, since exothermic peak are present at the temperatures $500\text{--}600^{\circ}\text{C}$. As a result the best resistance to crystallization characterizes the following glasses: LW-1, PBG08

and TCG75921. Within the limited range it is also possible to process the other glasses, especially TWPNI/6, but a risk of crystallization is high.

These six kinds of glass are characterized by different level of transmittance within the visible light range and the infrared (Fig. 3). Glasses PBG08 and TCG75921 offer high and broadband transmission alongside with good rheological properties.

Another significant technological issue is adhesion of the glasses to the mold surface during thermal treatment. Essential for this process is not only the viscosity but also the surface tension and the wetting between the glass and the material of the mold during embossing. We studied the interaction between all presented glasses and the mold material in the function of temperature to estimate their adhesion. The test glass pastilles were heated to the temperature of hemisphere point T_{pk} and cooled (without force) on a fused silica surface in the chamber of furnace. We observed that glasses LW-1, PBG05 and TWNB-1 permanently adhered to the mold surface. These glasses cannot be used for hot embossing with fused silica stamp. The remaining glasses, i.e. TCG75921, TWPNI/6 and PBG08 are suitable for embossing with fused silica stamp.

In conclusion, two glasses meet the requirements for the hot embossing process. These are lead–bismuth–gallium oxide glass PBG08 and lead–bismuth–tellurium–germanium oxide glass TCG75921. However, taking into account the cost of development we decided to choose for further study glass labeled PBG08 composed of $\text{SiO}_2\text{--PbO--Bi}_2\text{O}_3\text{--Ga}_2\text{O}_3\text{--CdO}$.

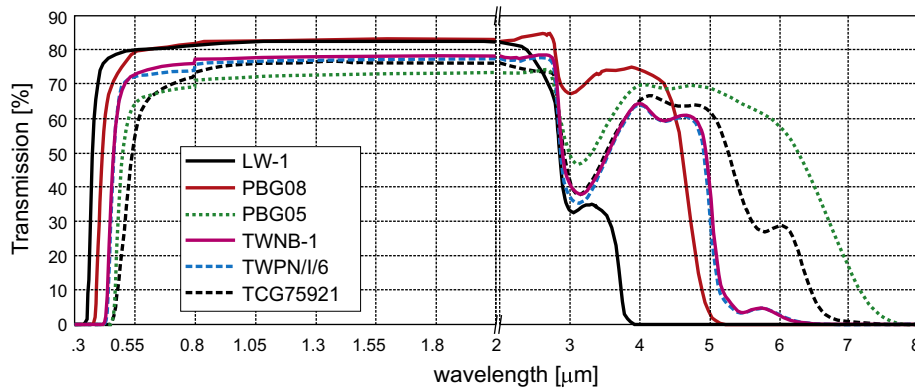


Fig. 3. Spectral transmission of the glasses for a 2 mm sample.

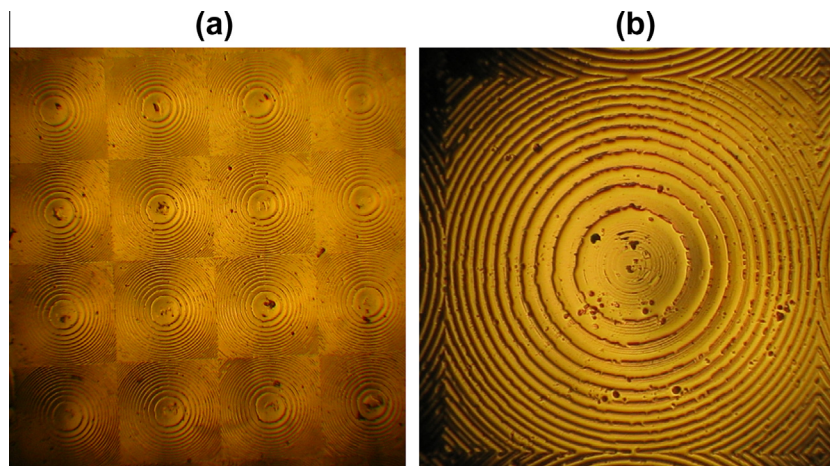


Fig. 4. Image of the array of the Fresnel lenses obtained from the optical microscope. Magnification $3.2\times$ (a) and $10\times$ (b).

3. Lens fabrication

In the case of diffractive elements used in mid-infrared the required thickness of the fabricated structure is within several micrometers, which is a huge technological challenge. That is why the molds were fabricated from quartz glass with the use of

ion etching technology (Fig. 4a). A single mold consisted of an array of 64 (8×8) of Fresnel lenses, each with a diameter of $750 \mu\text{m}$ (Figs. 4 and 5a).

To replicate the Fresnel lenses we used the hot embossing process presented in Fig. 1c. The choice of this method results of the low glass viscosity which forces a long time of the fabrication

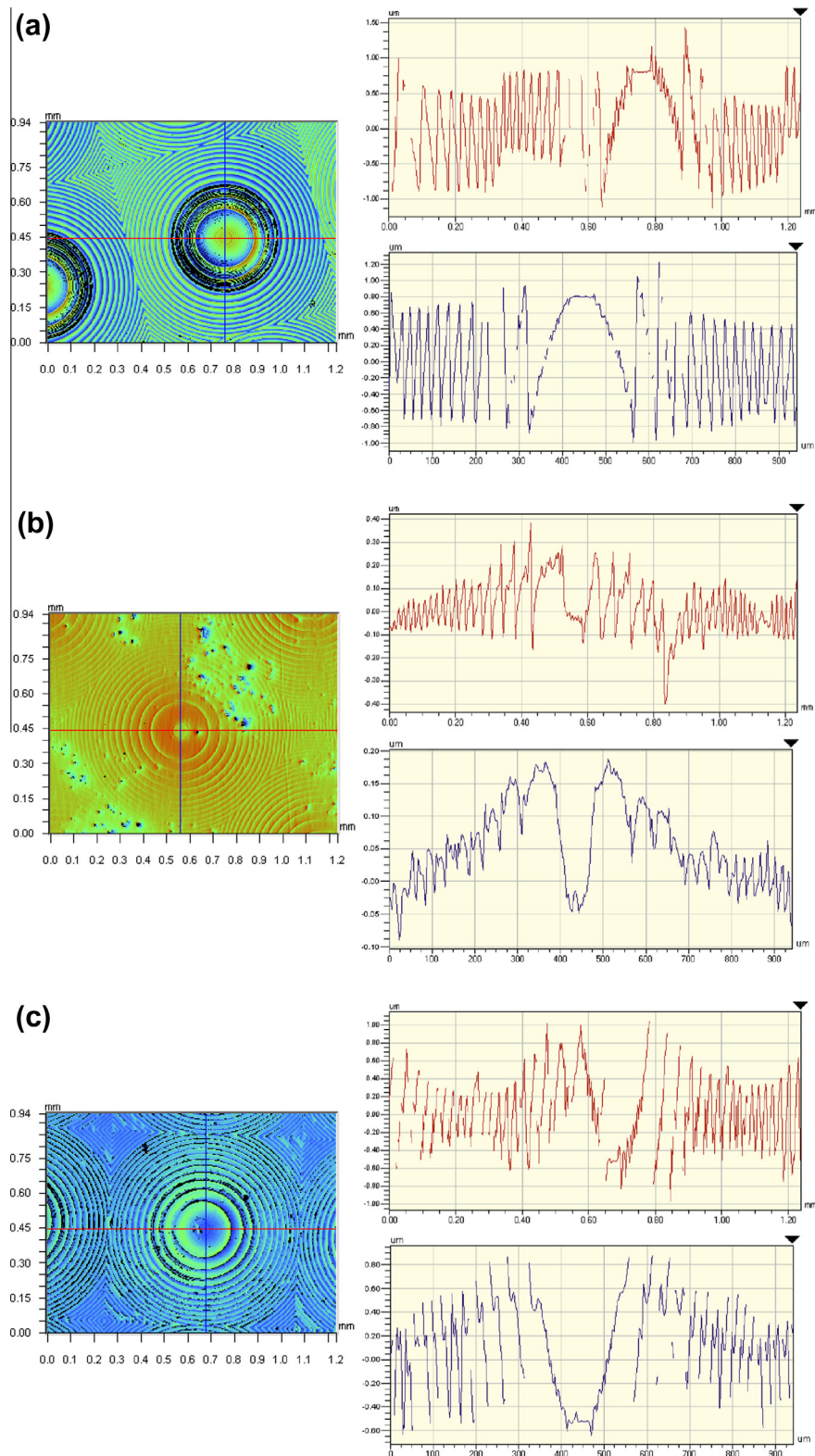


Fig. 5. Mould (a) and replicas (b), (c) made in the temperature of 518°C , force of 1.02 N for the different timing of the process: 40 min (b), 120 min (c).

process. The lenses were pressed out of round 2 mm thick glass samples made of the PBG08 glass, which were 2 cm in diameter. The quality of the replication of small elements in the Fresnel lens depends on the time, the pressure and the temperature of the replication process. The forming range for glasses is limited to the viscosity of 10^{13} – 10^9 (P). In the case when the viscosity is lower, the glass permanently adheres to the mold material. When the viscosity is too high the glass is not plastic enough and it does not fill in the tiny details of the form [1]. The imperfections in the replication visible in Fig. 4 are the result of local pollution of the stamp with dust particles. These distortions were transferred into replica during embossing process. During the process of unmolding such

distortions may cause local microstress leading to the emergence of flaws on the surface.

In order to investigate the influence of the parameters of the hot embossing process on the quality of the structures obtained we carried out several trials of element replication for the different temperature changes, time (up to 2 h) and force from 1.02 N to 1.34 N (equivalent pressure from 32.5 bar to 39.4 bar). In order to limit the adhesion of the glass to the mold material and for the separation of the sample from the mold, optimal parameters were the force of $F_s = 1.02$ N (pressure 32.5 bar), the temperature of the molding $T_s = 518$ °C and molding time of 120 min. It is worth remembering that the value of the T_s is not the same as the tem-

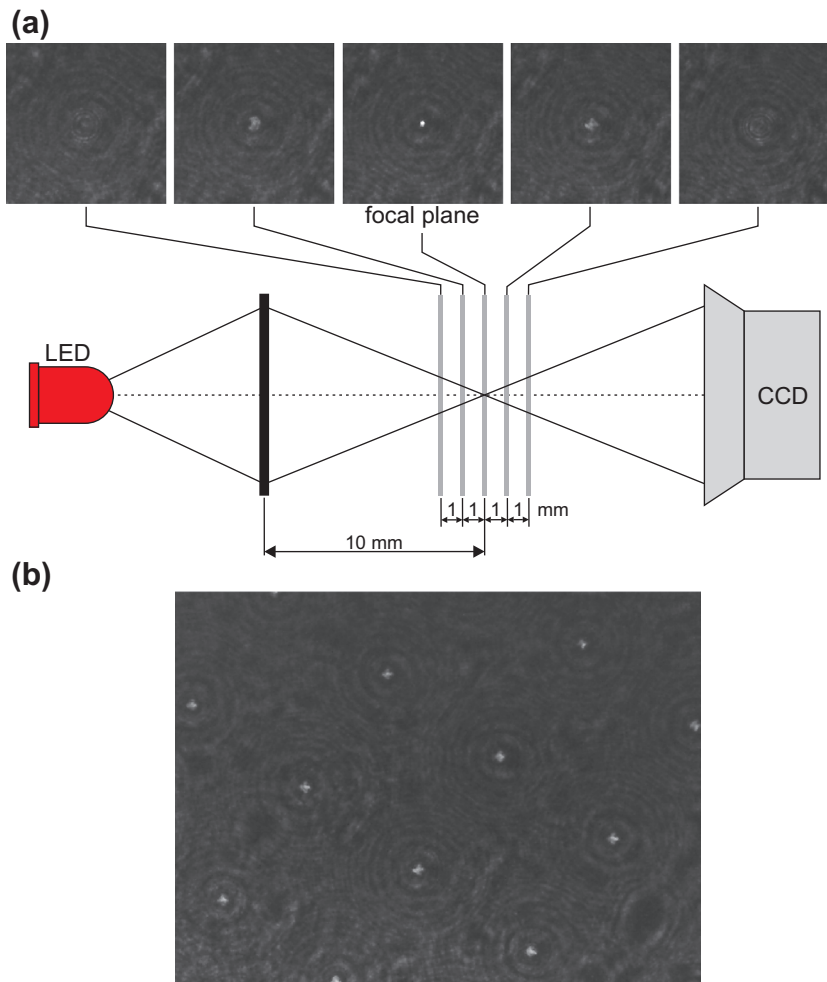


Fig. 6. Focusing light through the Fresnel lenses array. Light intensity at several planes for one Fresnel lens (a), and sample light intensity outside focal plane for array of lenses (b).

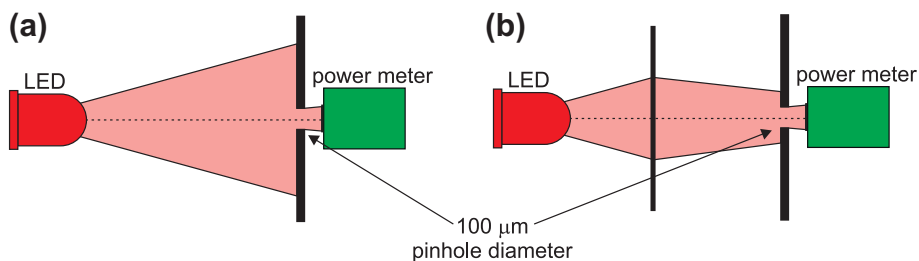


Fig. 7. Setups for examining the quality of the light focus.

perature of the substrate of PBGO8 glass obtained in the process. The temperature level of T_s depends on the construction of the oven, which determines the placing of the thermocouple, relative to the substrate. Further decrease of force in embossing process leads to errors in pattern transfer from the stamp onto glass sample. On the other hand, an increase of time beyond 120 min. caused problem with unmolding due to adhesion between the PBGO8 glass and fused silica glass. The selected force of $F = 1.02$ N that corresponds to 3.25×10^{-3} N/mm² is much lower than that typically used in hot embossing process for polymers (20–30 kN [7,9]) and chalcogenide glass (1000 N). This is related to higher crystallization tendency of heavy-metal oxide glasses as compared to polymer materials. As a result, if imprint force is increased, the PBGO8 glass tends to crystallize. With such a choice of the temperature and pressing, the quality of the elements obtained depended solely on the time of the hot embossing process. The example results of the replication for the two different periods of embossing time are presented in Fig. 5b and c.

The cross sections (Fig. 5) made with the use of white light interferometer (Veeco Wyko NT2000) prove that increasing the time of the process allows for the greater precision and creating elements of deeper structure. Such a dependency is easy to explain, as glass needs time to fill in the tiny details of the fabricated structure.

4. Focusing properties

For the fabricated Fresnel lenses, we carried out several optical measurements. They consisted in checking the quality of focusing within the visible light spectrum to mid-infrared. An example of the results obtained for light wavelength of $\lambda = 1300$ nm is presented in Fig. 6. The following images present the intensity of the light wave in the various planes around the focal plane of the Fresnel lenses, which in this case is 10 mm. Importantly, we obtained high homogeneity of light intensity in the particular foci, independent of their location. The largest experimentally measured difference does not exceed 10%. The quality of the focus of light was also measured in the system shown in Fig. 7. Regardless of the wavelength, the total power of light measured at the detector, was approximately three times higher when the Fresnel lens was used (Fig. 6b), relative to the system without the Fresnel lens (Fig. 6a).

The results obtained prove the focusing properties of the developed Fresnel lenses, although their performance is limited. However, to our knowledge, it is the first time that the development of Fresnel lens with hot embossing in soft glass has been reported. The previous papers reported only on the development of waveguides [12] and refractive lenses [4,8]. The degree of difficulty in replication of gray level microstructures is much higher than in case of binary structures of waveguides, or the continuous profile of lenses.

5. Conclusions

In the paper we have presented the results of experiments on fabricating glass diffractive elements for mid-infrared with the

use of a cost-effective method of hot embossing. As shown, an important drawback in using glasses with transmittance within visible light and mid-infrared is their rheology and proneness to crystallization. These disadvantages can be limited by widening the composition of the glass by adding oxides: GeO₂, SiO₂, Ti₂O, CdO, Nb₂O₅, etc., but this diminishes the spectral transmittance within the infrared. An additional problem is the proneness to adhesion of the glasses to the mold surface during the hot embossing process. From among the six types of glass considered we finally chose a five-component lead–bismuth–gallium oxide glass PBGO8. It is resistant to crystallization and is adhesive to the quartz glass of the mold only within a certain temperature range. The best results of replication were obtained for the process in the working temperature of 518 °C, with the use of low force of 1.02 N (pressure 32.5 bar) and for molding time of 120 min.

We have proved the ability of the lens to focus light in visible and in mid-infrared range. Summing up, the results of the optical measurements have shown that the hot embossing process is a time- and cost-effective way to produce glass diffractive elements to be used in mid-infrared optics.

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